CHAPTER VI

GROUND WATER SURVEY OF THE TEXAS GULF COASTAL PLAIN

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A. INTRODUCTION

The purpose of this investigation is to determine the availability of ground-water resources of the Gulf Coast Region, Texas, with particular reference to the sources of water suitable for the development of geothermal energy utilization for generation of electric power. For this purpose the availability of water resources is important for heat rejection. The expected characteristics of the geopressured geothermal resource* (lower temperatures) will result in low cycle efficiencies and hence large quantities of heat for rejection. Water resources will be very important, therefore, if evaporative cooling towers are to be used.

Figure VI-1 shows the Gulf Coast Region divided in five different subregions (adapted from Wood, 1971). Each subregion has similar soil formation, water availability, and general climatological characteristics. For the purpose of this investigation, each subregion will be studied individually on a county basis, one or two counties being studied as typical examples of each subregion. Sample counties are chosen according to data availability and location within the subregion. Table VI-1 lists the counties of the Gulf Coast Region, specifying the counties in each region. The counties that are underlined are the counties chosen as typical examples of each subregion.

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*Geopressure geothermal is a high pressure fluid source with enthalpies from 200 Btu/lb_m to 350 Btu/lb_m.

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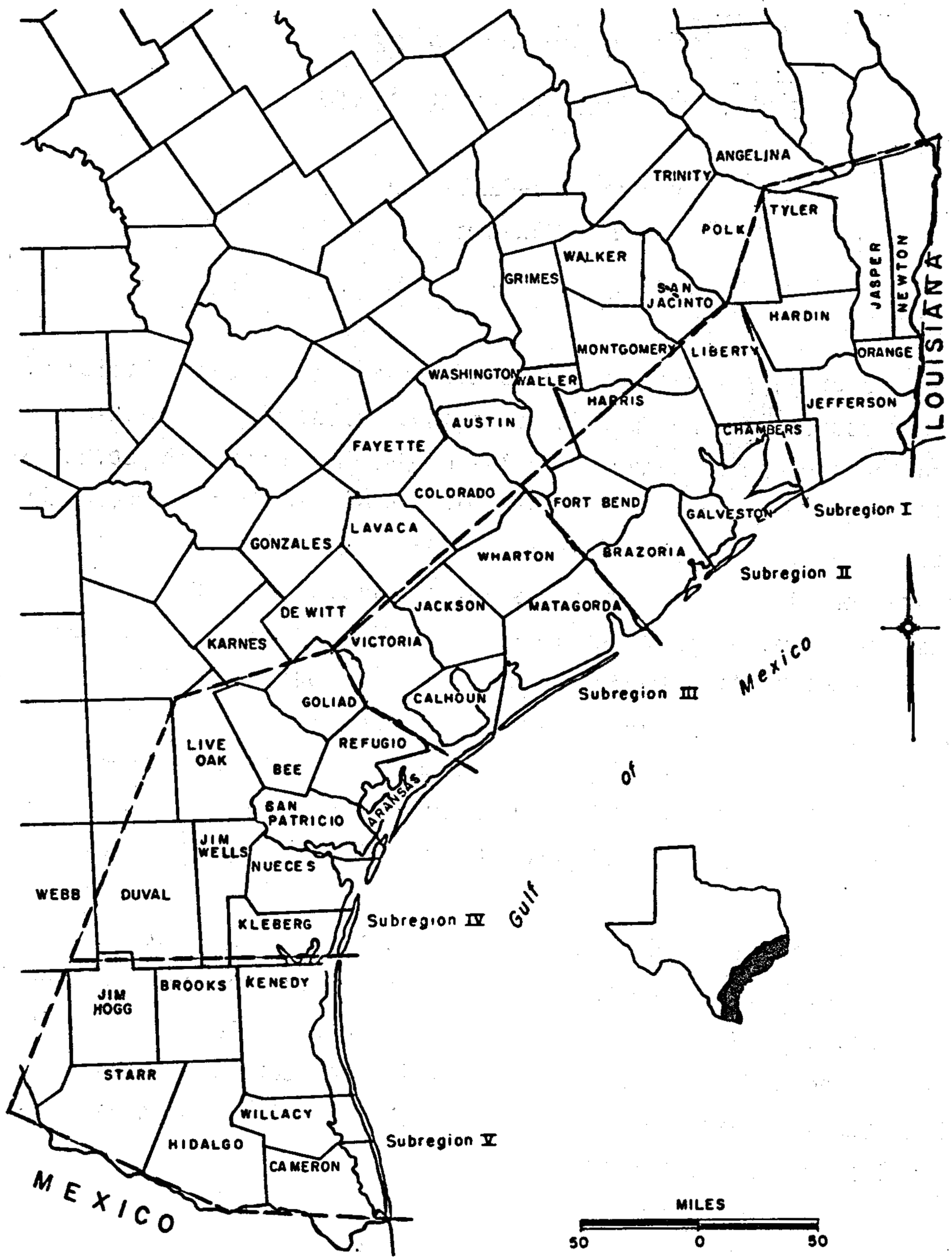

Figure VI-1. Map of Gulf Coast Region showing locations of subregions (Wood, 1971).

TABLE VI-1

COASTAL ZONE COUNTIES

SUBREGION				
I	II	III	IV	V
HARDIN	BRAZORIA	CALHOUN	ARANSAS	BROOKS
JASPER	CHAMBERS	JACKSON	BEE	CAMERON
JEFFERSON	FORT BEND	MATAGORDA	DUVAL	HIDALGO
NEWTON	GALVESTON	VICTORIA	GOLIAD	JIM HOGG
ORANGE	HARRIS	WHARTON	JIM WELLS	KENEDY
TYLER	LIBERTY		KLEBERG	STARR
			LIVE OAK	WILLACY
			NUECES	ZAPATA
			REFUGIO	
			SAN PATRICIO	

Counties underlined are typical samples of each region and are the ones that are studied in detail.

B. DESCRIPTION OF SELECTED COUNTIES IN THE TEXAS GULF COAST REGION

This section presents a brief description of the selected counties; special attention is given to the county location, areal size, population, and agricultural, mineral, industrial, and electric power production.*

Table VI-2 presents a summary of the geographic and economic characteristics of the thirty-five counties situated along the Texas Gulf Coast Plain. Approximately 3.5 million people live in this region of approximately 33,000 square miles. That is 35% of Texas' population in 12% of its land area. Hence, potable water is indeed going to be a commodity of great importance to this region and one which deserves considerable attention when planning future developments.

1. Subregion I - Jasper and Newton

Jasper and Newton counties are typical counties in Subregion I (Fig. VI-1). They are located along the eastern border of Texas near the Gulf of Mexico. Jasper County is bordered on the west by Hardin and Tyler Counties, on the south by Orange County, on the east by Newton County, and on the north by Angelina and San Augustine Counties. Newton County is bounded on the west by Jasper County, on the south by Orange County, on the east by Louisiana State, and on the north by Sabine County. Jasper County has an area of 969 square miles and a population of more than 25,000. Newton County is slightly smaller, has an area of 910 square miles and a population of more than 12,000.** Their combined area is 1,879 square miles and their combined population is more than 37,000. Newton County has a very small urban population. Jasper County's population is about 33% urban. Therefore, the two-county region has about 85% rural population. About 17% of the land is being cropped with about 0.3% being irrigated. The dollar value of crops and livestock is about 10 millions and dollar value of joint mineral production, including oil and gas, is more than 15 millions. The total net electrical power generation is about 400 million kw-hr per year. About 20 million dollars are added to the economy by manufacturers every year.

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*The electric power production is proportional to industrial production.

**Population data was taken in 1970 by U.S. Bureau of Census.

TABLE VI-2

SELECTED COUNTY CHARACTERISTICS OF THE GULF COAST REGION, TEXAS

COUNTY NAME	AREA SQUARE MILES	% CROPLAND HARVESTED	AVERAGE ANNUAL RAINFALL (inches)	% FARMLAND IRRIGATED	WATER USED FOR IRRIGATION 10^3 acre-feet/year	DOLLAR VALUE OF CROPS AND LIVESTOCK IN 1971 $\$10^6$	DOLLAR VALUE OF MINERAL PRODUCTION $\$10^6$	POPULATION		NET ELECTRIC POWER GENERATION PER YEAR (10^6 kw-hr)
								URBAN	RURAL	
HARDIN	895	17.2	52	1.7	4.7	<5	24	5,702	22,294	<0.1
JASPER	969	19.2	54	0.1	0.1	>5	5	6,251	18,441	233.4
JEFFERSON	945	37.2	53	20.3	177.4	13	45	232,393	12,380	2,289.2
NEWTON	941	14.7	56	0.5	1.0	<5	6	-	11,657	160.
ORANGE	356	38.6	54	5.4	10.3	<<5	5	47,146	24,024	7,921.6
TYLER	927	39.4	51	0.1	0.1	<<5	8	2,662	9,755	<0.1
BRAZORIA	1,441	39.4	48	11.5	21.8	13	200	66,392	41,920	<0.1
CHAMBERS	618	29.6	50	14.3	128.5	12	190	-	12,187	7,929.9
FORT BEND	862	53.1	46	7.1	85.9	19	90	29,074	23,240	6,685.3
GALVESTON	430	30.1	49	5.1	19.8	<5	48	151,744	18,068	<0.1
HARRIS	1,730	29.4	48	6.6	121.5	25	90	1,664,296	77,616	10,971.8
LIBERTY	1,173	42.4	50	9.5	101.8	13	40	15,022	17.992	0.1
CALHOUN	537	69.5	48	4.2	38.6	7	35	10,491	7,340	1,149.4
JACKSON	854	53.	40	6.7	116.4	12	87	5,332	7,643	<0.1
MATAGORDA	1,141	41.7	42	9.2	216.0	17	90	15,355	12,831	<0.1
VICTORIA	893	41.8	39	1.1	17.3	8	20	41,343	12,312	2,352.5
WHARTON	1,079	8.4	43	11.7	239.1	18	48	16,328	20,285	<0.1
ARANSAS	276	22.3	37	1.6	-	<5	15	4,605	4,297	<0.1
BEE	842	50.2	34	0.1	2.1	8	18	13,506	9,231	<0.1
DUVAL	1,814	34.3	24	0.4	2.4	6	48	6,563	5.159	<0.1
GOLIAD	871	17.5	28	0.6	1.3	8	20	-	4,869	<0.1
JIM WELLS	846	58.5	26	1.1	2.8	12	85	24,134	8,898	<0.1
KLEBERG	851	49.	28	0.2	0.6	6	150	28,711	4,455	<0.1
LIVE OAK	1,072	40.1	26	0.8	2.1	7	21	-	6,697	<0.1
NUECES	838	63.3	28	1.3	3.4	18	90	223,331	14,278	3,957.6
REFUGIO	771	51.2	32	-	-	7	88	4,340	5,154	<0.1
SAN PATRICIO	689	73.5	30	3.2	6.3	25	45	30,340	16,948	<0.1
BROOKS	904	22.4	24	0.4	1.0	>7	80	6,355	1,650	<0.1
CAMERON	883	68.8	19	63.6	414.6	60	6	108,805	31,563	1,032.8
HIDALGO	1,541	67.4	19	58.3	608.9	>75	32	134,521	47,014	945.6
JIM HOGG	1,143	17.7	20	0.3	1.5	<5	18	4,079	575	<0.1
KENEDY	1,407	68.8	26	0.1	0.2	<5	31	-	678	<0.1
STARR	1,207	50.8	<18	5.5	44.9	15	33	5,676	12,031	62.5
WILLACY	595	41.4	25	10.1	49.3	18	20	7,987	7,583	<0.1
ZAPATA	1,080	79.1	<18	1.1	8.8	<5	7	-	4,352	19.0

Note: The counties are listed by subregions as shown on Table VI-1.
Data from Arlingast, 1973 and Travis, 1974.

2. Subregion II - Fort Bend

Fort Bend County is located about 10 miles north of the Gulf of Mexico. Fort Bend County, which is adjacent to the Houston Metropolitan area, is bordered by Harris, Brazoria, Wharton, Austin, and Waller Counties. Fort Bend has an area of 862 square miles and a population of more than 52,000 (1970). About 60% of the Fort Bend population lives in urban areas; the principal city and county seat is Richmond. The value of crops and livestock was about 19 million dollars in 1971. About 50,000 acres were irrigated the same year and more than one half of the county area was cropped. The dollar value of the mineral production was over 90 millions. Electric power generation is more than 6,500 million kW-hr per year in Fort Bend County.

There are 5 large* manufacturing plants and about 65 small manufacturing plants in Fort Bend County. The value added to the county income by manufacturers is about 500 million dollars.

3. Subregion III - Jackson

Jackson County, with an area of 854 miles, is in the Gulf Coast region of South Texas and is about midway between Houston and Corpus Christi. Jackson County is bounded by Matagorda, Wharton, Lavaca, Victoria, and Calhoun Counties. Jackson County has a population of more than 13,000, of which about 60% live in rural areas. More than one half of the land is being cropped, but less than 7% is being irrigated. Jackson County has an average of 40 inches of rain fall per year. The dollar value of livestock and crops is about 12 millions, while mineral production is more than 80 millions. There is not a significant amount of electric power generation and there are not any important manufacturing industries in the county.

4. Subregion IV - Duval County

Duval County was selected as a typical example of Subregion IV even though it is located on the westerly edge of the geopressured geothermal zone.** Duval County is bounded on the south by Brooks and Jim Hogg

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*Large manufacturing plants have more than 250 employees.

**Duval County was chosen instead of Nueces County because a reasonable data base exists for the former whereas the latter does not have readily available data bases for ground and surface water resources.

Counties, on the west by Webb County, on the north by McMullen and Live Oak Counties, and on the east by Jim Wells County. San Diego, the county seat, is about 55 miles west of Corpus Christi. The county has an area of 1,814 square miles (1,160,960 acres); of this, only 9,500 acres are irrigated, while about 60,000 acres are appropriate for crops. The mean annual precipitation is about 24 inches, the consequences of which are that irrigation is required for production of some vegetables and fruits, and considerable cotton and hay. Production of grains is small.

The dollar value of crops in 1971 was about three millions and the dollar value of livestock was about six millions, while the mineral production (including oil and gas) represented 40 million dollars. Duval County has a population of more than 12,000, almost equally divided in rural and urban areas. Industry in Duval County is underdeveloped, contributing only about 5 million dollars per year to the county income.

5. Subregion V - Brooks County

Brooks County* is located in Subregion V in the southwest part of the Gulf Coast region. Brooks County is bordered on the north by Duval and Jim Wells Counties, on the west by Jim Hogg County, on the south by Hidalgo and Starr Counties, and on the east by Kenedy County. Brooks County has an area of 904 square miles and a population of about 9,000 that live principally in urban areas; less than 2,000 live in rural areas. The agricultural and livestock production has a value of more than seven million dollars, while the mineral production is about ten times larger, being over 75 million dollars in 1970. Brooks County is the richest county in Subregion V. There are no large electric power plants in Brooks County; electric power generation is negligible. There is no significant increase in the county income added by manufacturers. Industry is completely undeveloped in Brooks County.

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*Brooks County was chosen instead of Kenedy County because a reasonable data base exists for the former whereas the latter does not have readily available data bases for ground and surface water resources.

C. GROUND WATER RESOURCES

This section describes the ground water resources of each one of the counties selected for study as typical of each of the five subregions.

1. Subregion I - Jasper and Newton Counties

The geologic and hydrologic units that yield fresh or slightly saline water to wells in Jasper and Newton Counties are: the Jasper, Evangeline, and Chicot aquifers; the Yegua Formation, the Jackson Group, and the Catahuala Sandstone (Wesselman, 1967). The Jasper, Evangeline and Chicot aquifers crop out in Jasper and Newton Counties. The Jasper and Evangeline aquifers are separated by the Burkeville aquiclude (a tight clay formation containing little water and having a very low transmissivity).

a. Jasper Aquifer

The Jasper aquifer furnishes the water supplies for the towns of Jasper, Newton, Kirbyville, and Burkeville and for the community of Harrisburg. It supplies the water needs for all rural users in about a third of the Jasper and Newton Counties area.

The altitude of the base of the Jasper aquifer and the base of fresh water is about -5000 feet in the southern parts of Jasper and Newton Counties; the altitude of the base progressively increases northward to about -3000 feet in the area between Kirbyville and Bon Wier. Northward from this area the altitude of the base gradually increases to about -800 feet in an area near Jasper town and reaches the updip limit of the aquifer about ten miles from the northern boundaries of Jasper and Newton Counties.

In the northern parts of Jasper and Newton Counties, the sand thickness progressively increases southward to more than 900 feet in the area between Kirbyville and Bon Wier. Southward from this area the sand thickness continuously decreases to zero in the southern part of the counties.

The Jasper aquifer is the principal unit in the report area in terms of water storage, availability, quality, and potential for development. The coefficient of transmissibility ranges from 8,000 gpd per foot to 105,000 gpd per foot; the transmissibility of the entire thickness of the aquifer probably would be about 300,000 gpd per foot.

b. Evangeline Aquifer

The Jasper and Evangeline aquifers are separated by the Burkeville aquiclude (a clay bed that is usually 200 to 300 feet thick). The Evangeline aquifer in the Jasper and Newton Counties area includes sediments between the Burkeville aquiclude and the Chicot aquifer. In 1965, the Evangeline aquifer supplied more than 60% of the ground water used in Jasper and Newton Counties. The altitude of the base of the Evangeline aquifer is about -2000 feet in the southern part of the counties, the altitude of the base progressively increases northward reaching the updip limit of the aquifer 20 miles north of Kirbyville. The aquifer contains fresh water to depths of more than 1,500 feet below sea level in the area near the southern boundaries of Jasper and Newton Counties. The estimated thickness of fresh water sand in the Evangeline aquifer is more than 500 feet in the southern parts of Jasper and Newton Counties; the sand thickness decreases northward to about 100 feet in the area of Newton town. The coefficient of transmissibility of the Evangeline aquifer ranges from 16,000 gpd per foot to about 111,000 gpd per foot.

c. Chicot Aquifer

The Chicot aquifer supplies water for rice irrigation and domestic use to rural dwellings in the southern parts of Jasper and Newton counties and to the town of Burra. The altitude of the base of the Chicot aquifer is less than -600 feet in the southern boundaries of Jasper and Newton Counties; it increases northward to about -100 feet ten miles north of Kirbyville. The sand thickness of the Chicot is more than 400 feet in the southern part of the counties and decreases northward until the uplimit of the aquifer 10 miles north of Kirbyville. The artesian part of the Chicot aquifer begins near the northeastern corner of Hardin County, passes north of Kirbyville and out of Newton County in the vicinity of Salem and Big Cow Creek. The coefficients of transmissibility of the Chicot aquifer in Newton and Jasper Counties range from 92,500 gpd per foot to 510,000 gpd per foot.

d. Minor Hydrologic Units

i. Yegua Formation

The Yegua formation is not a source of fresh water in Jasper and Newton Counties. However, it contains small quantities of slightly to moderately saline water in the extreme northern parts of both counties. The altitude of the base of the Yegua formation is about -1,300 feet and the sand thickness is less than 300 feet.

ii. Jackson Group

Logs of nearby oil tests indicate that individual fresh-water-bearing sands as much as 20 feet thick occur at depths from 710 to 935 feet below land surface. The maximum sand thickness shown on one log is 40 feet. In places in northwestern Jasper County, the sandy beds in the Jackson Group are the only dependable source of fresh ground water. However, the presence or absence of these sands and the quality of the water in them can be detected only by test drilling.

iii. Catahuala Sandstone

The Catahuala Sandstone is overlain by younger sands in much of Jasper and Newton Counties. The altitude of the base of the Catahuala is at sea level in the northern boundaries of Jasper. The altitude of the base decreases southward to about -4000 feet in the area between Kirbyville and Bon Wier, which is the down-dip limit of the aquifer. The maximum sand thickness is less than 250 feet. In most of the area in Jasper County where the Catahuala contains fresh water, sands containing slightly to moderately saline water are interbedded with those containing fresh water.

2. Subregion II - Fort Bend County

Fresh water is available in Fort Bend County only from the Chicot and Evangeline aquifers (Wesselman, 1972). The Jasper aquifer is the deepest hydrologic unit in Fort Bend County, and contains some slightly saline water in the northwestern part of the county. About 120 million acre-feet of fresh water is in storage in these aquifers, and another 45 million acre-feet of fresh water is stored in the upper 500 feet of sediments.

a. Jasper Aquifer

The Jasper aquifer does not contain fresh water in Fort Bend County. The altitude of the base of the Jasper aquifer in the county is less than -2000 feet, and the maximum sand thickness is 100 feet. The coefficient of transmissibility of the aquifer is less than 11,000 gpd per foot in the Fort Bend area.

b. Evangeline Aquifer

The Evangeline aquifer supplies the water needs for rural and domestic users in about a third of Fort Bend County. The altitude of the base of the Evangeline varies randomly in the county area from -1600 feet to more than -3000 feet. The thickness of the sand bearing fresh water ranges from 100 feet to 600 feet, with an average of about 300 feet in Fort Bend County. The average coefficient of transmissibility is about 65,000 gpd per foot.

c. Chicot Aquifer

At most locations in Fort Bend County, water in the Chicot aquifer occurs under artesian conditions, but in the extreme northern part of the county, water levels have been lowered as much as 90 feet below the surface. The Chicot aquifer is the most important unit in Fort Bend County in terms of present water use.

The Chicot aquifer is subdivided into upper and lower units. In most of the southeastern part of the county, the two units are separated by a layer of clay, which is 200 to 300 feet below the land surface. The two units merge and generally function as a single aquifer in the northwestern part of Fort Bend County. The altitude of the base of the Chicot aquifer is -800 feet in the southern part of Fort Bend County and increases northward to about -300 feet. The average thickness of sand bearing fresh water is 350 feet and does not vary considerably throughout the county. The coefficients of transmissibility for the aquifer range from 13,200 to 126,000 gpd per foot.

3. <u>Subregion III - Jackson County</u>

In Jackson County, the ground water occurs in thick sequences of sand

and gravel, the dominant sediments forming the ground-water reservoir (Baker, 1969). The entire sequence of sediments functions as a single aquifer called the Gulf Coast aquifer. The Gulf Coast aquifer is the only fresh water bearing hydrologic unit in Jackson County. The water in the Gulf Coast aquifer occurs under artesian and water table conditions. The base of the fresh water ranges in depth from about sea level to at least 1,800 feet below sea level near Gavado. The deepest areas of fresh water are aligned in a trough-like depression trending southwestward from Gavado and passing slightly south of Edna. Northwestward from the trough, the depth of the base of the fresh water decreases to less than 400 feet just north of Jackson County in Victoria and Lavaca Counties. Southeastward from the trough, the deeper water becomes saline, causing the base of the fresh water to be shifted vertically upward, the shift exceeding 1,100 feet in places. South of the line of vertical shift, the depth to the base of the fresh water increases toward the east. The greatest thickness of the sands that contain fresh water is more than 1,200 feet and is located in the Gavado area. The amount of fresh water bearing sand thins progressively northwestward and southeastward from this area. The average thickness of sand containing fresh water is about 700 feet in Jackson County. The coefficient of transmissibility of the Gulf Coast aquifer ranges from 8,700 gpd per foot to 232,000 gpd per foot (In the Gavado area). The average coefficient of transmissibility of this aquifer is about 145,000 gpd per foot in Jackson County.

4. <u>Subregion IV - Duval County</u>

The geologic formations that yield fresh to slightly saline water in Duval County are the Catahuala Tuff, the Oakville Sandstone, and the Goliad Sand aquifers (Shafer, 1974). A brief description of each aquifer will follow:

a. Goliad Sand

Of the three aquifers, the Goliad Sand is by far the most heavily tapped by wells. The towns of Benavides, Concepcion, Realitos, and San Diego are supplied with water from wells in the Goliad Sand. All the wells in these towns are from 210 ft. to 750 ft. deep, and yield water having 730 to 1,390 mg/l dissolved solids. The wells have yields that range from

18 gpm (gallons per minute) to 420 gpm, although some of the irrigation wells in the Goliad Sand have reported yields as high as 1,800 gpm. The average transmissibility of sands bearing fresh to slightly saline water in the Goliad Sand is about 2,650 square feet per day. This is derived from an average sand thickness of 240 feet, and from an average hydraulic conductivity of 11 feet per day.

The formation of the Goliad Sands ranges in thickness from 0 to about 600 feet. In structurally undisturbed areas, the base of the Goliad dips southeastward at about 35 to 45 feet per mile. The altitude of the base in the southeastern part of the county is between 500 and 600 feet below mean sea level. The outcrop of the Goliad Sand of Pliocene age makes up more than half of the land surface in Duval County.

b. Oakville Sandstone

The Oakville Sandstone of Miocene age crops out in an irregular belt from 1 to 10 miles wide in the north-central part of Duval County. The Oakville ranges from 0 to about 600 feet in thickness, and dips southeastward at 60 to 80 feet per mile. Altitude of the top of the formation near the southeastern corner of the county is about 1,600 feet below mean sea level. The Oakville Sandstone yields small to moderate quantities of fresh to slightly saline water to rural-domestic, stock, and industrial wells in the county. An industrial well was reported to produce about 460 gpm of water from depth of 1,106 to 1,252 feet with the water containing 1,550 mg/l of dissolved solids.

Because the Oakville occurs at a greater depth than the Goliad Sand (which is a more productive aquifer that has water of better quality), the development of ground water supplies from the deeper Oakville Sandstone has been slow.

c. Catahuala Tuff

The amount of water available for development from the Catahuala Tuff is difficult to determine because of lack of appropriate data on the aquifer in Duval County. However, there were water-level measurements made in 1969-1970 in the well-field that supplies water to Freer. It found a hydraulic gradient of about 15 feet per mile, an average transmissivity of the sands bearing fresh to slightly saline water to about 1,200 square feet per day. This approximation was derived from an average sand thickness of 80 feet.

5. Subregion V - Brooks County

The rock formations that contain fresh to slightly saline water include the Oakville Sandstone, Lagarto Clay, Goliad Sand, Lissie Formation, and the Beaumont Clay (Myers, 1967).

a. Oakville Sandstone

The Oakville is capable of yielding moderate quantities of water where the sand is sufficiently thick. Much of the formation contains saline water in Brooks County. The Oakville crops out in north-central Duval County, about 35 miles north-northwest of Brooks County. The altitude of the base of the Oakville ranges from -1000 to about -2500 feet in Brooks County. The maximum thickness of the sand bearing fresh water is 500 feet in Brooks County, but the average thickness of the sand is very small in the county.

b. Lagarto Clay

The Lagarto is capable of yielding small quantities of water to wells in Brooks County. The Lagarto Clay overlies the Oakville Sandstone and has a maximum thickness of about 700 feet that dips east-southeast toward the coast.

c. Goliad Sand

The Goliad Sand is the most important water bearing formation in Brooks County, and yields most of the water used in the county. The Goliad Sand, which overlies the Lagarto Clay, crops out in northwestern Brooks County. The altitude of the base of the aquifer is about -1000 feet in the northeast part of the county, increasing radially in all directions. The average altitude of the base of the aquifer is about -500 feet in the central and southeast parts of Brooks County. In the western part of the county, the base of the Goliad is very shallow and crops out in several places. The maximum thickness of the sand that contains fresh water is about 1000 feet, but generally the thickness of the water bearing sands has not been precisely determined because of the lithologic similarity of the formations above and below it.

d. Lissie Formation

The Lissie Formation, overlying the Goliad Sand, crops out in northcentral Brooks County. The remainder of its outcrop is covered by windblown sand.* The Lissie formation has a maximum thickness of around 300 feet at the eastern edge of the county and is found at different depths. Small quantities of water sufficient for domestic and livestock needs may be obtained from the Lissie, but the water in many places is highly mineralized.

e. Beaumont Clay

The Beaumont Clay overlies the Lissie Formation; it has a maximum thickness of 100 feet and yields small quantities of mostly highly mineralized water to a few domestic and livestock wells.

*The windblown sand is white to pale tan, fine to very fine grained, well sorted, round to sub-angular, and unconsolidated. It contains saline water and ranges in thickness between 0 - 60 feet in Brooks County.

D. GROUND WATER AVAILABLE FOR DEVELOPMENT

This section reviews the expected ground water available for development in each one of the counties taken as representative of the five Texas Gulf coast subregions.

1. Subregion I - Jasper and Newton Counties

The volume of ground water available for development (without depleting the storage level in the outcrops below stream level) is dependent upon the rate of recharge of the aquifer. The principal source of fresh ground water is precipitation on the outcrops of the aquifers. Much of this precipitation runs off as stream flow. Part of its is evaporated at the land surface, transpired by plants, or retained by capillary forces in the soil; the remainder moves downward by gravity through the zone of aeration to the zone of saturation. In this zone, the rocks are saturated with water in the different aquifers. Note that in the entire area of Jasper and Newton Counties (1,879 square miles), which have an average annual precipitation of more than 50 inches, there is an annual precipitation on the aquifer outcrops of more than 4 million acre-feet. Of this amount, about 14% could be stored in the aquifers. An immense quantity of ground water is in transient storage in the two counties. About 500,000 acre-feet per year is being discharged from the aquifers as base flow for the different springs, creeks, and the Sabine River. More than 70,000 acre-feet per year is presently transmitted from the aquifer for different uses. This means that at least 570,000 acre-feet per year could be developed without depleting the storage level of fresh water in the aquifers below stream level.

The 570,000 acre-feet per year rate gives some conception of the magnitude of water supply that can be safely developed on a continuous basis from the aquifers in Jasper and Newton Counties.

2. Subregion II - Fort Bend County

Fort Bend County (an area of 862 square miles) has an annual average precipitation of 44 inches. The capacity of recharge of the aquifers is about 10%; therefore, there are about 200,000 acre-feet of fresh water which are recharged into the aquifers every year. About 120 million acre-feet of fresh water are stored in the aquifers and another 45 million acre-feet in the upper 500 feet of sediments.

Calculations based on the aquifer characteristics lead to the conclusion that 168,000 acre-feet per year are continuously available for development; that amount is several times the present quantity of water which is transmitted from the aquifers. The average thickness of the sand bearing fresh water is about 650 feet and lies at depths of less than 3,000 feet.

Ground water use is an essential factor in the economic development of Fort Bend County, but only a small part of this resource is presently being used.

3. Subregion III - Jackson County

About 95 million acre-feet of fresh ground water is in storage in Jackson County; however, most of this is not available for development because of the great depth at which it occurs and because a large fraction of the water cannot be drained from the sands. To make use of at least part of the water in storage, the aquifer could be pumped at a rate of 300 million gallons per day for a period of perhaps 75 years without serious consequences.

The present rate of pumpage is equal to or larger than the rate of recharge to the Gulf Coast aquifer in Jackson County. Ground-water levels are declining at an average rate of about 1.5 feet per year, and will continue to decline as more ground water is pumped, but the relatively large rainfall (38 inches per year) in the area probably is adequate to provide the aquifer with sufficient water to offset the present rate of pumpage (more than 85 mgpd) and eventually stabilize the decline. That is, as water levels continue to decline, recharge from rain water should increase owing to increased short term storage available in and near the aquifer's outcrop.

4. Subregion IV - Duval County

The volume of ground water available in Duval County on a long-term basis depends on the average rate of recharge of the aquifers. The long-term average rate of recharge can be estimated by determining the quantity of ground water, in each aquifer, which moves through the county.

This quantity is computed by using the formula:

$$Q = T\ I\ W \qquad \text{Eq. 1}$$

where

Q = Quantity of water moving through the aquifer in million gallons per day or acre-feet per year.

T = The coefficient of transmissibility in gallons per day per foot.

I = Original hydraulic gradient of the water surface in feet per mile.

W = Is the average width of the county in miles, normal to the hydraulic gradient of the aquifer.

Table VI-3 shows the total ground water available for development in Duval County.

TABLE VI - 3

GROUND WATER AVAILABLE FOR DEVELOPMENT IN DUVAL COUNTY

AQUIFER	W (miles)	T (gpd per foot)	I (ft per mile)	Q (mgpd)
GOLIAD SAND	56	2,650	9	10
OAKVILLE SANDSTONE	56	1,680	10	7
CATAHUALA TUFF	48	1,200	15	6
TOTAL GROUND WATER AVAILABLE FOR DEVELOPMENT = 23 mg/d				

$$Q_{Total} = 23 \times 10^{6} \times \frac{360}{\text{year}} \times 3.07 \times 10^{-6} \text{ acre-feet}$$

$$Q_{Total} = 25{,}420 \ \frac{\text{acre-feet}}{\text{year}}$$

5. Subregion V - Brooks County

Following the same procedure used in Duval County we can calculate the quantity of ground water moving through the county. Table VI-4 shows the collective aquifer characteristics and the ground water available in Brooks County for perennial development.

TABLE VI-4

GROUND WATER AVAILABLE FOR DEVELOPMENT IN BROOKS COUNTY FROM COLLECTIVE AQUIFERS

AQUIFER CHARACTERISTICS	Q = T I W
T = 13,000 gpd per foot	Q = 5,140,000 gpd
I = 12 feet per mile	1 gpd = 1.105×10^{-3} $\frac{\text{acre-feet}}{\text{year}}$
W = 33 miles	Q = 5,680 $\frac{\text{acre-feet}}{\text{year}}$

In addition to at least 5,600 acre-feet per year perenially available for withdrawal, about 80 million acre-feet of fresh to slightly saline water is in transient storage in the county. Because most of this water is too deep in the ground to be withdrawn economically, only the water stored in the upper part of the aquifer will be considered for potential development. About 10 million acre-feet of water in transient storage could be withdrawn from the upper 400 feet of saturated sediments. That depth is considered to be an "economic" depth.

E. WATER REQUIRED TO DEVELOP GEOTHERMAL POWER

Wells drilled for geothermal geopressured fluids may use standard oil field procedures, with water-based drilling fluids used for the entire borehole. The mud used as drilling fluid may consist of different qualities of water and different kinds of clay; the quantity of water required for the well construction is not very significant, although it should not be ignored.

Large quantities of cooling water may be required for efficient electric power generation. One MW of continuous power could require as much as 100 acre-feet of cooling tower makeup water per year. However, substantially reduced cooling-water requirements are possible. In a flashed-steam process, mineral-free steam condensate is produced. In some areas it may be possible to use the cooled geothermal brine as cooling tower makeup, if the salt content is low. The use of dry cooling towers may also be possible if water is in short supply.

The design of a geothermal power plant is restricted to the temperature and pressure of the geothermal fluids. It is a relatively simple matter to design a plant that will work under the conditions set by the geothermal fluid and by the ambient temperature*; it may not be simple to provide a design which generates electricity in an economically competitive manner. In the process of optimization the engineer must make many decisions regarding the following factors:

1. Selection of a Working Fluid

Steam may be the cheapest working fluid, but, for low enthalpy fluids, will usually result in a lower efficiency and will require a larger amount of cooling water. The optimum fluid will depend upon the reservoir temperature. For low enthalpy reservoirs, a secondary working fluid process may be attractive. Propane (boiling point = -44°F) might be used in a low temperature reservoir, while hexane (boiling point = $+150^{\circ}$F) might be the best fluid in a higher temperature reservoir; there may be a fluid (mixture

*Note that the practical heat sink temperature is 55 to 60°F in Winter and 75 to 80°F in Summer.

of different fluids) that will optimize the design of the geothermal power plant.*

2. Selection of Condensing Temperature and Cooling System

The lower the condensing temperature, the higher the efficiency of the plant. This temperature will vary with the method of cooling as well as local climate conditions. Table VI-5 illustrates the different cooling techniques and the amount of water required to run each system. These calculations have been made assuming an average year temperature of 70°F, a minimum winter temperature of 20°F, and a maximum summer temperature 105°F. This is the annual temperature range expected in the Texas Gulf Coastal Plain.

TABLE VI-5

ESTIMATED WATER REQUIREMENTS FOR ALTERNATIVE COOLING TECHNIQUES** FOR 50 MW(e) [NET] ELECTRIC GENERATION (GEOTHERMAL)

COOLING TECHNIQUE	WATER REQUIREMENTS			LAND ACRES
	THRU-PUT (GAL/MWH)	CONSUMPTION (PER MW)		
		GAL/MWH	ACRE-FEET / MW-YEAR	
ONCE THROUGH	225,000	1384	38	0.0
COOLING PONDS	225,000	1395	39	420
WET TOWERS	225,000	4219	113	3.0
DRY TOWER	0	-	-	4.5

*Research is being done in order to find a model that will identify the optimum fluid (mixture) for a given reservoir temperature. Fluid properties are evaluated using Starling, 1973.

**Cooling water requirements are based on projections made from data concerned with the cooling water requirements used in geothermal plants in California, with appropriate correlations for the Texas Gulf Coastal Plain climatology and expected geothermal fluids quality. Adapted from Fulton, 1974, and Underhill, 1975.

Dry cooling towers have the advantages of eliminating the discharge of waste heat to natural water bodies and eliminating cooling water requirements, except for possible minor makeup water to replace leakage in systems using water as working fluid. Dry cooling towers are not nearly as efficient as evaporative cooling towers and thus require a substantially larger investment to accomplish the same amount of cooling. Dry systems operate with backpressures of up to 15 in. of mercury that result in loss of generating capability of the power plant. In a hot climate, dry towers are very inefficient, reducing the power production of the power plant considerably (up to 30%).

Some power plants using evaporative cooling towers operate efficiently at ambient temperatures as high as 110^{o}F. The cooling water needed to operate a 50 MW(e) power plant could be more than 3,500 acre-feet per year if wet towers are used.

Mitigations to this problem include having wet tower cooling during peak loads or tremendously oversizing the dry towers* to provide adequate cooling during peak periods. However, neither of these alternatives is economically attractive. It has been suggested that a combination of the dry tower with the evaporative tower may increase efficiency and reduce the makeup water considerably. The wet/dry tower would be designed for water conservation, which is of utmost interest in much of the Gulf Coastal Plain. To construct a wet/dry tower to accomplish this will probably require considerable additional capital and operating expense compared to that required for ponds or evaporative towers. A scheme not addressed above is the saline cooling pond (or ponds) with makeup from the geothermal fluids themselves. In some areas, it may be possible to use the cooled geothermal brine as cooling-tower water makeup if the salt content is low. Proper conversion cycle and cooling process selection can result in little or no requirement for cooling water makeup. However, this objective must be viewed in terms of the local needs for power, of local water use trade-off studies, and of local economic conditions.

Should saline water be considered for once-through cooling with cooling ponds, it is important to note that such ponds cannot be located in

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*Oversizing dry towers represents an economic burden presently not acceptable.

shallow or deep ground water aquifer recharge zones. In other locations, the ponds would require liners and leakage detection systems. On the other hand, use of saline water in evaporative cooling towers places restrictions on tower performance because of the requirements for minimizing saline fluids drift. Tower fill would also be subjected to deposition of solids which would result in a slow degradation of tower performance. The high salinity fluids blown down from the tower would have to be disposed of in an environmentally acceptable manner.

F. PRESENT AND EXPECTED FUTURE USES OF WATER IN THE TEXAS GULF COAST REGION

Table VI-6 shows a summary of ground water pumpage in the Gulf Coast region during 1959. Water use has been increasing considerably in the last 15 years; Table VI-7 shows an approximation of the ground water used in 1970. The data on this latter table are not very accurate because of lack of information about some counties' ground water uses. The agricultural production is proportional to the quantity of water available; therefore, in regions where the rainfall is small, large amounts of ground water are required for irrigation. It is seen that a large amount of ground water is being used for irrigation. The amount of water used for public supply is small and is proportional only to the population; the future needs of ground water for public supply will be established by population growth.

Industrial production requires a lot of electric power and small to large amounts of ground water, depending on the industry. It can be seen that the counties which have high electric power production, have high industrial production regardless of the amount of water available.

1. Subregion I - Jasper and Newton Counties

Jasper and Newton Counties are using about 60,000 acre-feet of ground water per year of which more than 80% is being used by the Evadale Paper Mill. The remainder of industrial use is less than 1,000 acre-feet per year of ground water. There is some rice farming which uses about 2,000 acre-feet per year. The remaining ground water developed is used for domestic and rural public supply and livestock.

It is very difficult to make projections of future ground water uses in Jasper and Newton Counties. Future ground water use depends on the industrial and agricultural development in the area as well as population growth. Jasper and Newton Counties have an annual average precipitation of 55 inches; therefore, agricultural development will not necessarily depend only on ground water production. However, the paper industry needs a large amount of water to operate; if an expansion of this industry occurs in Jasper and Newton Counties, ground water uses will increase considerably.

TABLE VI-6

SUMMARY OF GROUND WATER PUMPAGE IN THE GULF COAST REGION, 1959

SUB-REGION	PUBLIC SUPPLY acre ft./yr.	INDUSTRIAL acre ft./yr.	IRRIGATION acre ft./yr.	MISCELLANEOUS acre ft./yr.	TOTAL acre ft./yr.
I	5,500	43,000	23,000	7,800	80,000
II	140,000	130,000	120,000	11,000	390,000
III	14,000	25,000	220,000	9,000	270,000
IV	15,000	8,200	10,000	6,000	40,000
V	6,400	1,700	130,000	4,400	140,000
TOTAL	180,000	210,000	500,000	38,000	920,000

SOURCE: Texas Water Commission, Bulletin 3605, p. 101.

*Totals are approximate because most figures in the table have been rounded to two significant figures and totals are further rounded to two significant figures.

TABLE VI-7

SUMMARY OF GROUND WATER PUMPAGE IN THE GULF COAST REGION, 1970

SUB-REGION	PUBLIC SUPPLY acre ft./yr.	INDUSTRIAL acre ft./yr.	IRRIGATION acre ft./yr.	MISCELLANEOUS acre ft./yr.	TOTAL acre ft./yr.
I	6,000	91,000	193,600	8,200	298,800
II	148,000	301,000	430,300	13,100	942,400
III	14,700	64,000	627,400	10,500	716,600
IV	16,100	15,100	21,200	6,300	58,700
V	6,800	2,300	1,129,200	4,700	1,143,000
TOTAL	191,600	473,400	2,451,700	42,800	3,159,500

SOURCE: Texas Water Development Board

2. Subregion II - Fort Bend

The use of ground water has increased greatly since 1900 in Fort Bend County; Table VI-8 shows the estimated pumpage of ground water in Fort Bend County in 1968, 1971, and expected future utilization.

TABLE VI-8

ESTIMATED PUMPAGE OF GROUND WATER IN FORT BEND COUNTY

USE	WATER USED IN		MAXIMUM WATER USE EXPECTED IN:
	1968 (acre-feet)	1970 (acre-feet)	2020 (acre-feet) *
INDUSTRIAL	15,200	18,400	28,400
MUNICIPAL	5,600	6,100	11,600
IRRIGATION	43,900**	85,200***	126,000
RURAL-DOMESTIC & LIVESTOCK USE	1,500	1,600	2,000
TOTAL	66,000	116,000	168,000

*This model implies that the development of geothermal energy will develop local industry and agriculture faster than would be projected without geothermal energy development.

**Wesselman, 1972.

***Travis, 1974.

3. Subregion III - Jackson

Table VI-9 shows the quantity of ground water pumped for irrigation, industry, public supply, and rural-domestic and livestock needs in Jackson County in 1963 and 1970. The present rate of pumpage in Jackson County equals the maximum amount of ground water available for development without depletion. As explained in section D.3., there is a large amount of ground water in storage in Jackson County, but it is not certain when this water will be available for development.

TABLE VI-9

PUMPAGE OF GROUND WATER IN JACKSON COUNTY

USE	WATER USED IN	
	1963 (acre-feet)	1970 (acre-feet)
INDUSTRIAL	88,100	116,400
MUNICIPAL	1,940	2,200
IRRIGATION	1,380	1,600
RURAL-DOMESTIC & LIVESTOCK USE	729	∿ 800
TOTAL	92,000	121,000

4. Subregion IV - Duval County

There are 13,000 people living in Duval County; 7,000 people live in urban areas and the rest in rural areas. The land that is irrigated is prolific; about 9,500 acres are irrigated and there are more than 300,000 acres that are arid and have high productivity potential if irrigated. It is necessary to increase the area irrigated to increase the production of crops. If good irrigation methods are used, 0.25 acre-feet per acre annually will be enough to make the land productive.* Table VI-10 shows how the water was used in 1970 in Duval County, and two models of expected future water uses. Model A assumes** geothermal energy development for electric power generation; this model assumes the construction of a 50 MW(e) geothermal power plant that will use wet towers for waste-heat rejection. Model B assumes no water consumption for power generation; that means no power generation or power generation with no water consumption (if research verifies feasibility).

TABLE VI-10

WATER USE DISTRIBUTION IN DUVAL COUNTY***

USE	WATER USED IN 1970 (acre-feet)	MAXIMUM WATER USE EXPECTED IN YEAR 2020	
		MODEL (A) (acre-feet)	MODEL (B) (acre-feet)
PUBLIC SUPPLY	1,110	3,000	3,000
RURAL AND DOMESTIC STOCK	850	1,200	1,200
IRRIGATION	2,500	14,100	18,000
INDUSTRIAL	1,480	3,200	2,800
GEOTHERMAL POWER PRODUCTION	-	3,500	-
TOTAL	5,940	25,000	25,000

*2500 acre-feet of water were used to irrigate about 9,500 acres in 1970.

**Geopressured, geothermal resource fairways are not currently identified in Duval County; these two models were evaluated for this county in order to illustrate the impact of 50 MW(e) of geothermal power generation on a typical Region V county.

***Expectations of water uses are projections of the rate of change in water uses since 1955. Model A includes the expected increment of industrial and agricultural development with the future electric power production by geothermal energy.

Note that Model B has 3,900 more acre-feet of water for irrigation than Model A; this statement means that if Model B occurs, 72,000 acres could be irrigated; while if Model A occurs, only 56,400 could be irrigated. Thus, generation of electric power using wet towers with ground water makeup will displace irrigation at the rate of 280 acres per megawatt. The 3,500 acre-feet per year of evaporative cooling water makeup is estimated on the basis of 50 MW(e) generation using the most consumptive technology. Other technology might be economic, in which case tower makeup could be greatly reduced or zero. For this latter case both irrigation and generation could be accomodated to some degree.

5. Subregion V - Brooks County

The use of ground water in Brooks County approximately doubled from 1932 to 1964. Since 1964, the use of ground water has been 4,100 acre-feet per year. The quantity used for public supply has increased rapidly, but irrigation declined accordingly. Table VI-11 contains data on pumpage of ground water in 1964 and 1970 and a model of the maximum quantity of ground water that could be developed in Brooks County without depletion.

TABLE VI-11

PUMPAGE OF GROUND WATER IN BROOKS COUNTY

USE	WATER USED IN		MAXIMUM WATER USE EXPECTED IN:
	1964 (acre-feet)	1970 (acre-feet)	2020 (acre-feet)
PUBLIC SUPPLY	1,345	1,700	2,080
IRRIGATION	1,675	1,200	2,200
INDUSTRY	224	280	320
RURAL DOMESTIC & LIVESTOCK NEEDS	874	920	1,000
TOTAL	4,100	4,100	5,600

G. IMPACT OF GEOTHERMAL ENERGY ON WATER RESOURCES IN THE TEXAS GULF COASTAL PLAIN

The principle concerns of geopressured geothermal energy development which involve water resources are ground water contamination and availability and use of potable water resources. Ground water resources can be contaminated by improper drilling procedures and by pipeline or ponded saline fluids leaking into ground water recharge areas. The presence of geothermal generating facilities can require large quantities of potable water and hence can have a very significant impact on water resources in large regions of the Gulf Coast Plain.

Protection of ground water resources during and subsequent to drilling activities will require procedures commonly employed in the oil and gas industry for that particular purpose. In general, oil and gas practice has been very effective and will be effective for the geopressured geothermal resource as well. Thus, the major possibilities for ground water contamination arise from surface ponding of geothermal fluids and gathering and dispersal system operation.

Many areas along the Gulf Coast Plain contain aquifer recharge areas as discussed previously. Other areas contain large surface sand zones which act as recharge areas for shallow, local ground water storage. These areas present specific problems with respect to ponding and fluid transmission systems. Careful design and monitoring can minimize the potential local impact, but cannot totally eliminate the possibility of ground water contamination.

The development of geothermal energy could affect considerably the ground water reserves of a particular region. As noted previously, the development of geothermal energy may or may not require large amounts of water depending on the plant design. But the development of geothermal energy could lead to the development of industries that use a lot of water. The development of industries which would consume a lot of water would be prohibitive in regions of scarce ground water resources.

Cycle selection and heat rejection system design can mitigate the requirements for potable water. For example, if subsidence mitigation and water resources conservation are mutually important, then a secondary working fluid cycle with dry cooling (aided by an evaporative tower during hot weather) may be an appropriate design choice. Consequently, research activity having as object the investigation of similar design alternatives is highly desirable and recommended for Phase 1 activities.

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